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# STUDIES OF THE MAJOR PLANET SATELLITE SYSTEMS

HERBERT FREY  
PAUL D. LOWMAN

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**(Telephone 301-982-4488)**

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SATELLITE SYSTEMS

Herbert Frey  
Geophysics Branch  
Earth Survey Applications Division  
NASA/Goddard Space Flight Center  
Greenbelt, Maryland 20771

and

Astronomy Program  
University of Maryland  
College Park, Maryland

and

Paul D. Lowman  
Geophysics Branch  
Earth Survey Applications Division  
NASA/Goddard Space Flight Center  
Greenbelt, Maryland 20771

## STUDIES OF THE MAJOR PLANET SATELLITE SYSTEMS

The next phase of planetary exploration will include a major effort aimed at an understanding of the outer solar system: Jupiter, the ringed planet Saturn, Uranus, Neptune, and Pluto, together with their satellites and the properties of the interplanetary medium and solar wind at distances exceeding 5 astronomical units. Not the least among these are the satellites of the jovian planets, which offer much that is new to our previous experience with the inner solar system, but which may also fill in some of the missing pages in the early chapters of the evolution of bodies like the Earth, the Moon and Mars whose recent history we are now able to read.

Below we present a summary of the available data on the satellites of the major planets, including the currently most plausible models for several observed phenomena. The review is not meant to be exhaustive nor historical, but rather is intended to establish the present state of knowledge which is available to those planning spacecraft missions to these objects. In the final section we detail some of the important questions likely to be solved by flyby and/or orbital missions to the giant planets, and indicate the importance of these studies to our understanding of the solar system as a whole.

PART I

PROPERTIES OF THE OUTER PLANET SATELLITES

## I. ORBITAL CHARACTERISTICS

The orbital characteristics of the satellites of the outer planets are reasonably well established. Table I lists the semimajor axis, eccentricity, inclination referred to the planetary equator (except for the Saturn system which is referred to the ring plane) and sidereal period of revolution for each of the known satellites of Jupiter, Saturn, Uranus and Neptune. The data are from the review article by Newburn and Gulkis (1973). The eccentricity and inclination columns suggest two distinct classes of satellites: those with nearly circular ( $e < 0.1$ ) orbits in the plane of the planet's equator ( $i < 2^\circ$ ), and those with highly eccentric, highly inclined (including  $i > 90^\circ$ , or retrograde) orbits. The former are generally referred to as "regular" and the latter are called "irregular".

Regular satellites are commonly considered natural by-products of planetary formation, much as the planets are considered natural consequences of the origin of the sun. It is known, though not completely understood, that the first seven planets and the asteroids obey the numerical relation called the Titius-Bode Law. The major satellites of the giant planets follow a similar pattern. Figure I plots the semimajor axis of the planets on a logarithmic scale (curve b) below that predicted by a Titius-Bode Law (Allen, 1963).

TABLE I. ORBITAL DATA FOR SATELLITES

SATELLITE	SEMI-MAJOR AXIS ( $10^3$ km)	ECCENTRICITY	INCLINATION ( $^{\circ}$ )	SIDEREAL PERIOD (days)
J V	181.5	0.0028	$0^{\circ} 27.3$	0.4982
J I Io	422.0	0.0000	$0^{\circ} 1.6$	1.7691
J II Europa	671.4	0.0003	$0^{\circ} 28.1$	3.5512
J III Ganymede	1,071.0	0.0015	$0^{\circ} 11.0$	7.1546
J IV Callisto	1,884.0	0.0075	$0^{\circ} 15.2$	16.6890
J VI	11,487.0	0.158	$27.6$	250.57
J VII	11,747.0	0.207	$24.8$	259.65
J X	11,861.0	0.130	$29.0$	263.55
J XII	21,250.0	0.169	$147$	631
J XI	22,540.0	0.207	$164$	692
J VIII	23,510.0	0.378	$145$	739
J IX	23,670.0	0.275	$153$	758
S X Janus	168.7	0	$0^{\circ} 0$	0.815
S I Mimas	185.8	0.0201	$1^{\circ} 31.0$	0.9424
S II Enceladus	238.3	0.0044	$0^{\circ} 1.4$	1.3702
S III Tethys	294.9	0	$1^{\circ} 5.6$	1.8878
S IV Dione	377.9	0.0022	$0^{\circ} 1.4$	2.7369
S V Rhea	527.6	0.0010	$0^{\circ} 21$	4.5175
S VI Titan	1,222.6	0.029	$0^{\circ} 20$	15.9455
S VII Hyperion	1,484.1	0.104	$(17^{\circ} 56')$	21.2767
S VIII Iapetus	3,562.9	0.0283	$14.72$	79.3308
S IX Phoebe	12,960.0	0.1633	$150.05$	550.45
U V Miranda	129.8	0.01	$0^{\circ} ?$	1.4135
U I Ariel	190.9	0.0028	$0^{\circ} ?$	2.5204
U II Umbriel	266.0	0.0035	$0^{\circ} ?$	4.1442
U III Titania	436.0	0.0024	$0^{\circ} ?$	8.7059
U IV Oberon	583.4	0.0007	$0^{\circ} ?$	13.4633
N I Triton	355.55	0	$159^{\circ} 95$	5.8768
N II Nereid	5,567.0	0.7493	$27.71$	359.881

Inclinations  $> 90^{\circ}$  indicate retrograde motion relative to the planetary spin direction.

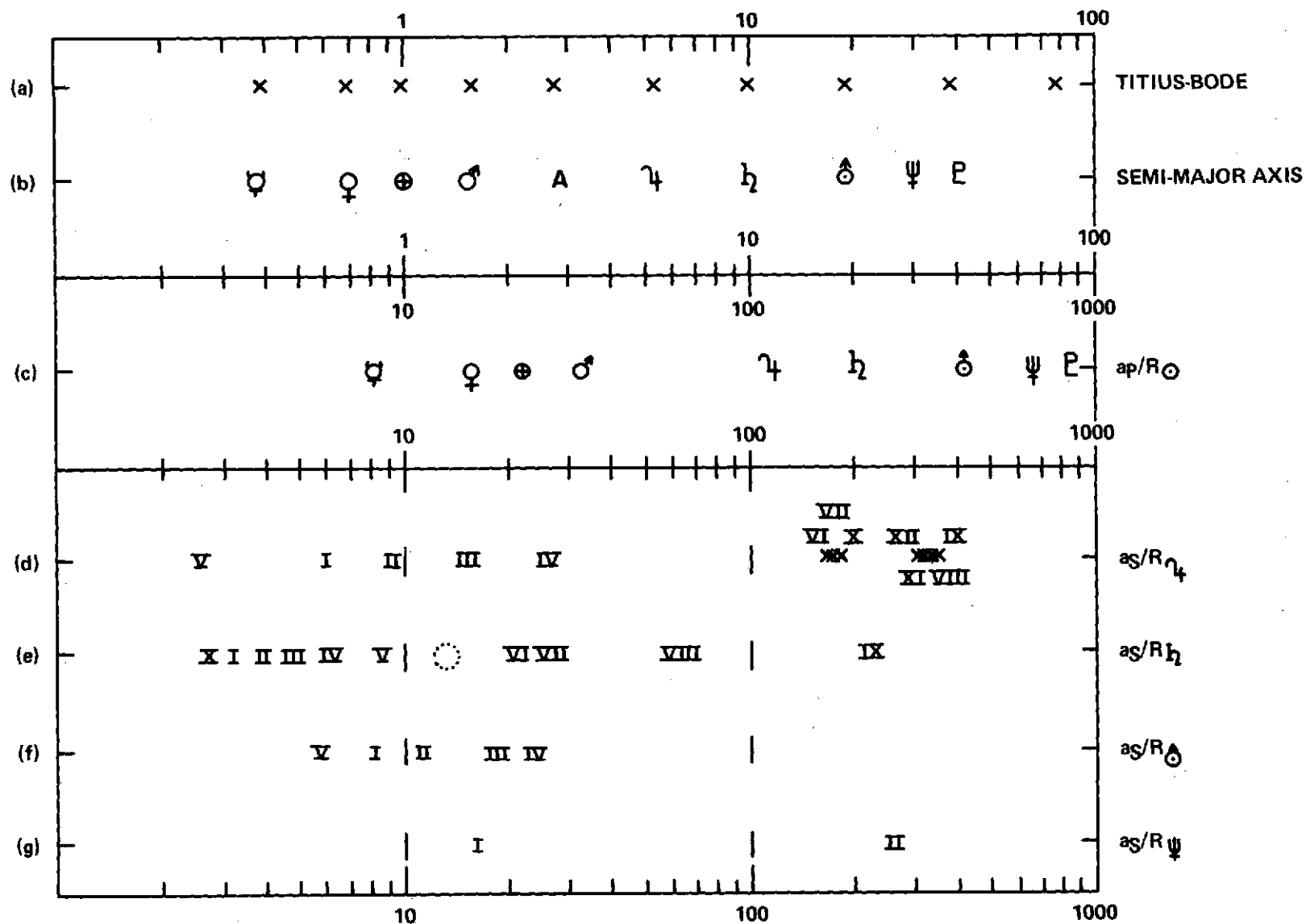


FIGURE 1. Distance of planets from the sun and of satellites from the primary. (a) Semi-major axes of the planets predicted by a Titius-Bode relation. (b) Semi-major axes observed for the planets. (c) Semi-major axes of the planets in units of the radius of the sun. (d - g) Semi-major axes of the satellites in units of the planetary radius for the satellites of (d) Jupiter, (e) Saturn, (f) Uranus, and (g) Neptune.



Note the excellent agreement through Uranus. Curves c through g plot the semimajor axis of the planets (c) or satellites (d,e,f,g) divided by the radius of the sun (c) or primary planet Jupiter (d), Saturn (e), Uranus (f) and Neptune (g). The pattern similarity is striking: regular satellites like JI-V are clearly separated from irregular ones such as JVI-XII. Note the gap in the Saturn system between Rhea (SV) and the massive Titan (S VI); a similar gap occurs in the solar system proper between Mars and Jupiter. Black (1971) has studied the above relations in a quantitative way and predicts the existence of an "asteroid belt" in the Saturn system at  $a = 7.9 \times 10^5$  km ( $a/R_p = 13.1$ ). This point is marked by the open circle in curve e.

In a similar way it is possible to speculate on the existence of one or more faint, undiscovered satellites of Uranus at  $a/R_p \sim 3$ .

It is difficult to understand the orbital characteristics of satellites like J VI-XII in terms of in situ formation around Jupiter, especially for the retrograde moons J VIII, IX, X and XI, and S IX (Phoebe). Irregular satellites are generally regarded as captured bodies. Baily (1971) has described a mechanism whereby direct orbit capture at Jupiter's perihelion leads to semimajor axes around  $11.5 \times 10^6$  km. Retrograde orbits result from capture at Jupiter's aphelion and lead to orbits of  $27 \times 10^6$  km semimajor axes.

Table I and Figure I show the close correspondence between these predictions and the observed semimajor axes of the outer jovian satellites. A detailed study is lacking for Saturn, but it is likely that Phoebe is a captured object.

Nereid (N II) is in a high eccentricity (0.75), inclined ( $27^{\circ}7'$ ) orbit, but is not necessarily a captured body. McCord (1966) believes the orbit of Nereid may result from interaction with Triton, Neptune's massive, retrograde satellite. The orbital history of Triton suggests a possible capture origin for the satellite (McCord, 1966), although the Pluto-Triton interaction suggested by Littleton (1936) is not excluded. The tidal decay of Triton's orbit will lead to its destruction in a relatively short period of time, 10-100 million years according to McCord's calculations.

Iapetus (S VIII) and Hyperion (S VII) of Saturn represent uncertain cases, not easily classified as either regular or irregular satellites. Figure II is a plot of  $\sin i$  versus eccentricity (on a logarithmic scale) for the moons of the outer planets. Retrograde motions are assigned a negative ( $\sin i$ ). While Iapetus has a relatively high inclination ( $14^{\circ}7'$ ), its eccentricity is no greater than that of Titan (0.028). At its distance from Saturn, the orbit of Iapetus experiences equal perturbations from (a) the sun, and (b) the oblateness of Saturn and Titan's mass. These



competing effects keep Iapetus out of both the plane of the ecliptic and out of the equatorial plane of Saturn (Brouwer and Clemence, 1961). The inclination of this satellite is therefore constrained by its position in the Saturn system, and is not necessarily a condition of capture.

In Figure II, Hyperion (S VII) is seen to lie nearly in the plane of the inner satellites of Saturn. The eccentricity, however, is large (0.1), and the satellite lies unusually close to massive Titan (Figure 1). While the origin of Hyperion is uncertain, its present orbit is very much under the influence of Titan, whose mean daily motion is in 4:3 ratio with the smaller satellite. Porter (1961) points out that this causes conjunctions of the two satellites to always occur at the same place in Hyperion's orbit - the aposaturn point. With extended observations of the orbit of Hyperion it should be possible to accurately determine the mass of Titan.

Many satellites share orbital commensurabilities. For example, the mean daily motions of J I, II and III satisfy the relation of  $n_I - 3n_{II} + 2n_{III} = 0$ . The four large inner satellites of Saturn have mean motions in the ratio 6:4:3:2, but neither Rhea nor Titan are part of this commensurability (Porter, 1961). Titan's motion is commensurate with Hyperion,

as discussed above, but Rhea does not share any low order commensurability with any other Saturn satellite (Brouwer and Clemence, 1961). These complex interactions must be considered when relating an observed phenomenon to the position or motion of a single satellite.

No direct evidence is available on the rotation periods of the satellites of the outer planets. Observations of a single minimum and a single maximum in the light curves of the satellites J I-IV (Harris, 1961; Johnson, 1971) and S III, IV, V and VIII (McCord et al., 1971) suggest synchronous rotation. Titan shows essentially no variation with rotational phase (Blanco and Catalano, 1971). These results are in agreement with the available visual observations of those satellites large enough to present disks (Lyot, 1953; Dollfus, 1961). It is generally assumed that most all satellites rotate synchronously with their revolution about the primary planet.

## II. PHYSICAL PARAMETERS

The masses and radii of the satellites of the giant planets are in general poorly known. Only the Galilean satellites and Titan present measurable disks (Dollfus, 1970), and indirect methods must be employed to estimate the radii of other moons. The common technique of assuming an albedo

and deriving a diameter from the measured brightness of the object is quite unsatisfactory. Direct measurements of the satellites of Mars by Mariner 9 television imaging showed these objects to be some 75% larger than previously thought (Pollack et al., 1972). The errors were due to an overestimate of the albedo (see Zellner, 1972a). There is no information available on limb darkening, inhomogeneities in surface coloration or irregularities in shape for the smaller satellites. Many of the larger satellites do show surface features (Lyot, 1953) and brightness variations with orbital phase (Harris, 1961; Johnson, 1971; McCord et al., 1971). Recent stellar occultation of Io (Taylor, 1972; O'Leary and Van Flandern, 1972) and of Ganymede (Carlsen et al., 1973) have provided improved diameters for these two objects. In both cases the new radii are some 100-300 km larger than previously believed. Diameters of asteroids determined from photometry and infrared radiometry (Morrison, 1973; Cruikshank and Morrison, 1973) are generally 30-40% larger than the visual determinations by Dollfus (1971).

It is also difficult to determine the masses of small bodies. Accurate masses of the principle planets are required, and these depend on the mass of Jupiter and on one another (Duncombe et al., 1973). Studies of mutual perturbations among satellites of the same system offer promise of improved values only for those masses which dominate the system

(Brouwer and Clemence, 1961). Contributions from the sun and those due to the figure of the planet are both important for orbital changes of the satellites. In the Saturn system, the unknown mass of the rings is another problem. It is therefore not surprising that the mass of J IV (Callisto) is known to less than 10%, and that of Rhea to less than 50%, since these two objects share no commensurabilities with other satellites.

Table II presents the best available data (through 1 January 1974) for the masses and radii of the satellites of the Jovian planets. The masses are from Duncombe et al. (1973), and the radii are from Newburn and Gulkis (1973) except where noted. The mass ( $7.347 \times 10^{25}$  gm) and radius (1737.63 km) of the moon are from Haines (1971). The densities are calculated from Table values, assuming a spherical shape.

Preliminary tracking data analysis from Pioneer 10 indicates the mass of J I (Io) should be increased 15-20% (Anderson et al., 1974). This revises the density given in the Table upwards to  $3.5 \text{ gm/cm}^3$ . Furthermore, Gehrels (1974) reports the densities of all four Galilean satellites as 3.48, 3.07, 1.94 and 1.65 for J I-IV. The values quoted in Table II are then too low for J I and J IV.

The exceptionally high densities calculated for J VII (15.9), S IX Phoebe (7.1) and the satellites of Uranus (20.9, 11.6, 15.7, 8.4 and 9.5) and Neptune (12.1 and 8.5)

TABLE II. PHYSICAL DATA FOR SATELLITES

		MASS			RADIUS		DENSITY
SATELLITE		M ( $10^{24}$ gm)	M / M <sub>P</sub>	M / M <sub>J</sub>	R (km)	R / R <sub>J</sub>	(gm/cm <sup>3</sup> )
J V		0.0034	$18 \times 10^{-10}$	0.00005	70 <sup>a</sup>	0.04	2.38
J I	Io	78.868	$4.15 \times 10^{-5}$	1.073	1830 <sup>b</sup>	1.053	3.07 <sup>p</sup>
J II	Europa	47.629	$2.51 \times 10^{-5}$	0.648	1550 <sup>c</sup>	0.892	3.05 <sup>p</sup>
J III	Ganymede	153.426	$8.08 \times 10^{-5}$	2.089	2640 <sup>c</sup>	1.520	1.99 <sup>p</sup>
J IV	Callisto	91.098	$4.80 \times 10^{-5}$	1.240	2500 <sup>a</sup>	1.440	1.39 <sup>p</sup>
J VI		0.0016	$8.5 \times 10^{-10}$	0.00002	50 <sup>a</sup>	0.03	3.08
J VII		0.00007	$0.35 \times 10^{-10}$	0.000001	10 <sup>a</sup>	0.006	15.87
J X		0.000002	$0.01 \times 10^{-10}$	0.00000003	7 <sup>a</sup>	0.004	1.32
J XII		0.000001	$0.07 \times 10^{-11}$	0.00000002	6 <sup>a</sup>	0.003	1.47
J XI		0.000004	$0.02 \times 10^{-10}$	0.00000005	8 <sup>a</sup>	0.005	1.77
J VIII		0.000015	$0.08 \times 10^{-10}$	0.0000002	10 <sup>a</sup>	0.006	3.49
J IX		0.000003	$0.02 \times 10^{-10}$	0.00000004	8 <sup>a</sup>	0.005	1.33
S X	Janus	---	---	---	---	---	--
S I	Mimas	0.0375	$6.59 \times 10^{-8}$	0.00051	235 <sup>d</sup>	0.27	0.69
S II	Enceladus	0.0842	$0.15 \times 10^{-8}$	0.00115	275	0.16	0.97
S III	Tethys	0.6226	$1.10 \times 10^{-6}$	0.00847	600	0.35	0.69
S IV	Dione	1.1594	$2.04 \times 10^{-6}$	0.01578	410	0.24	4.02
S V	Rhea	1.8195	$3.20 \times 10^{-6}$	0.02477	650	0.37	1.58
S VI	Titan	139.9820	$2.46 \times 10^{-4}$	1.9053	2425 <sup>a</sup>	1.40	2.34
S VII	Hyperion	0.1137	$0.20 \times 10^{-6}$	0.00155	200 <sup>a</sup>	0.12	3.39
S VIII	Iapetus	2.2403	$3.94 \times 10^{-6}$	0.03059	650 <sup>a</sup>	0.37	1.95
S IX	Phoebe	0.0296	$5.20 \times 10^{-8}$	0.00040	100 <sup>a</sup>	0.06	7.06
U V	Miranda	0.0874	$1 \times 10^{-6}$	0.00119	100 <sup>a</sup>	0.06	20.86
U I	Ariel	1.3109	$15 \times 10^{-6}$	0.01784	300 <sup>a</sup>	0.17	11.59
U II	Umbriel	0.5244	$6 \times 10^{-6}$	0.00714	200 <sup>a</sup>	0.12	15.65
U III	Titania	4.3697	$50 \times 10^{-6}$	0.05948	500 <sup>a</sup>	0.29	8.35
U IV	Oberon	2.5344	$29 \times 10^{-6}$	0.03450	400 <sup>a</sup>	0.23	9.45
N I	Triton	339.5251 <sup>n</sup>	$3.3 \times 10^{-3n}$	4.62128 <sup>n</sup>	1885 <sup>a</sup>	1.09	12.10 <sup>n</sup>
N II	Nereid	0.03539	$0.34 \times 10^{-6}$	0.00048	100 <sup>a</sup>	0.06	8.45

<sup>a</sup>Data taken from Allen(1963)<sup>b</sup>From stellar occultation(O'Leary and Van Flandern,1972)<sup>c</sup>From stellar occultation(Carlson et al, 1973)<sup>d</sup>Value very uncertain.<sup>p,n</sup>See text



reflect the uncertainties in the measured values. A factor 2 increase in the radius of J VII or U II reduces the density by  $1/8$  to approximately  $2 \text{ gm/cm}^3$ . Smaller increases in the radii of the other small satellites would also lower the densities to more reasonable values. Such increases are not at all unlikely in view of the available techniques for determining radii of small and faint objects.

The mass of Triton reported by Duncombe et al. (1973) is nearly three times that given by Newburn and Gulkis (1973). Assuming the radius is correct as given, the lower mass yields a density of  $4.5 \text{ gm/cm}^3$ .

Accurate densities are very important for constructing interior models of these objects. High density bodies ( $\rho > 3$ ) are probably rocky, silicate structures; low densities ( $\rho < 2$ ) suggest a large percentage of ices. Lewis (1971a,b) has proposed models of the Galilean satellites which make these bodies very unlike our own moon. The recent Pioneer result suggesting 3.5 for Io (Anderson et al., 1974) may indicate that this object at least is of the more familiar type found in the inner solar system. The density gradient in the satellites decreasing outward from Jupiter bears a qualitative similarity to that seen in the terrestrial planets, and may have important cosmogonic implications.

### III. SPECTROPHOTOMETRIC STUDIES

The first compilation of UBVRI magnitudes and colors for the satellites of the major planets was by Harris (1961). The effective wavelengths of the filters used in this study are:

TABLE III. WAVELENGTHS OF U B V R I FILTERS

	U	B	V	R	I
$\lambda$ ( $\mu$ )	.35	.45	.55	.69	.82

Table IV incorporates the data of Harris (1961) as reported by Newburn and Gulkis (1973) except as noted. The apparent magnitude at mean opposition,  $m_V$ , is from Allen (1963). The absolute visual magnitude at zero phase and reduced to unit distance from Earth and from Sun,  $V(1,0)$ , is calculated from the relation (Harris, 1961),

$$V(1,0) = V_0 - 5 \log a(a-1)$$

where  $a$  is the semimajor axis of the planetary orbit.

The Galilean satellites, Titan and Triton are much brighter in  $V(1,0)$  than the other satellites because of their large size. Io is clearly a very red object, and Titan is redder than most. Titania and Oberon are comparatively blue.

TABLE IV. MAGNITUDES AND COLORS FOR SATELLITES

SATELLITE	$m_V$	U - B	B - V	V - R	R - I	V(1,0)
J V	+13	--	--	--	--	---
J I Io	5.5	1.30	1.17	0.66	0.32	-1.89
J II Europa	5.8	0.52	0.87	0.57	0.31	-1.52
J III Ganymede	5.1	0.50	0.83	0.59	0.31	-2.15
J IV Callisto	6.3	0.55	0.86	0.61	0.32	-1.19
J VI	14	--	--	--	--	---
J VII	18	--	--	--	--	---
J X	19	--	--	--	--	---
J XII	19	--	--	--	--	---
J XI	19	--	--	--	--	---
J VIII	18.5	--	--	--	--	---
J IX	19	--	--	--	--	---
S X Janus	13.5 <sup>d</sup>	--	--	--	--	---
S I Mimas	12.1	--	--	--	--	+2.5 <sup>r</sup>
S II Enceladus	11.7	--	0.62	--	--	+2.21
S III Tethys	10.6	0.34	0.73	--	--	+0.71
S IV Dione	10.7	0.30	0.71	0.48	0.32	+0.88
S V Rhea	10.0	0.35	0.76	0.61	0.26	+0.20
S VI Titan	8.3	0.75	1.29	0.84	0.11	-1.21
S VII Hyperion	14.5	0.42	0.69	--	--	+4.60
S VIII Iapetus	11	0.28	0.71	--	--	+1.47
S IX Phoebe	14	--	--	--	--	---
U V Miranda	16.9	--	--	--	--	+3.8
U I Ariel	14	--	--	--	--	+1.7
U II Umbriel	15	--	--	--	--	+2.6
U III Titania	13.8	0.25	0.62	0.52	0.41	+1.29
U IV Oberon	14.0	0.24	0.65	0.49	0.33	+1.48
N I Triton	13.6	0.40	0.77	0.58	0.44	-1.23
N II Nereid	19.5	--	--	--	--	---

<sup>d</sup>Dollfus(1967)<sup>r</sup>Russell et al(1945)

The colors and magnitudes of Table IV are mean values. Harris (1961) also reported brightness variations for the Galilean satellites. The single minimum and maximum in the visual light curve seems to confirm the synchronous rotation first suggested from visual observations of surface features by Lyot (1953). The variations for the large satellites of Jupiter (Harris, 1961) are summarized below:

TABLE V. BRIGHTNESS AND COLOR VARIATIONS  
FOR THE GALILEAN SATELLITES

	$\Delta V$	$\Delta (B-V)$	$\Delta (U-B)$
J I (Io)	0.21	0.18	0.50
J II (Europa)	0.34	0	0.19
J III (Ganymede)	0.16	0	0.04
J IV (Callisto)	0.16	0	0

Owen and Lazor (1973) find small color variations in their photometric system (similar but not identical to the U B V system) for all the satellites except for B'-V' for Europa.

For J I, II and III the leading hemisphere is both the brighter and the bluer; the trailing side of Callisto (J IV) is the brighter. Furthermore, Callisto shows no brightness change at small solar phase angles. From opposition to a solar phase of  $\alpha = 10^\circ$  the V magnitude of J IV changes by  $\sim 0.6$  at rotational phase  $\theta = 140^\circ$ , but by only 0.4 magnitudes at  $\theta = 250^\circ$ .

Iapetus (S VIII) of Saturn displays unusually large brightness variations from one hemisphere to the other. Millis (1973) confirms the 2 magnitude change in V and finds only small variation in B-V (0.07) and U-B (0.045). The depths of successive minima however, change by some 0.3 magnitudes in the light curve, which he attributes to a greater effect of solar phase for the leading, darker side than on the brighter, trailing hemisphere.

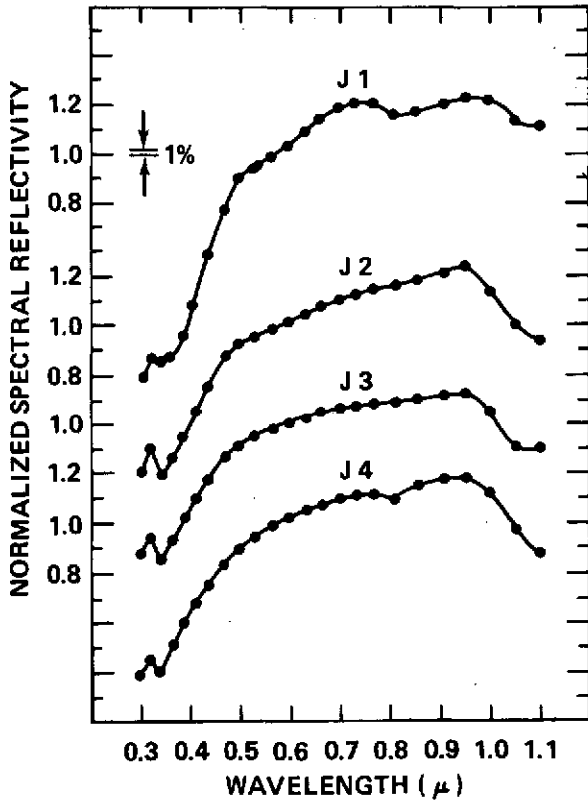
McCord et al. (1971) report variations in the reflectivity of Saturn's satellites Tethys, Dione and Rhea, and confirm the large change in brightness for Iapetus. Titan does not appear to vary, although Blanco and Catalano (1971) find more scatter in their observations than expected. For Tethys, Dione and Rhea the leading side is the bright side; for Iapetus the leading side is darker than the trailing side.

According to visual observations by Steavenson (1950), Titania, Oberon and probably Ariel of Uranus show variable brightness. The satellites of Neptune have not been shown to vary in either magnitude or color.

Johnson (1971) and Johnson and McCord (1970) have carried out detailed photometry of the brighter satellites of Jupiter from 0.3 to  $1.1\mu$  using a series of evenly spaced, medium bandwidth (0.02 to  $0.05\mu$ ) interference filters.

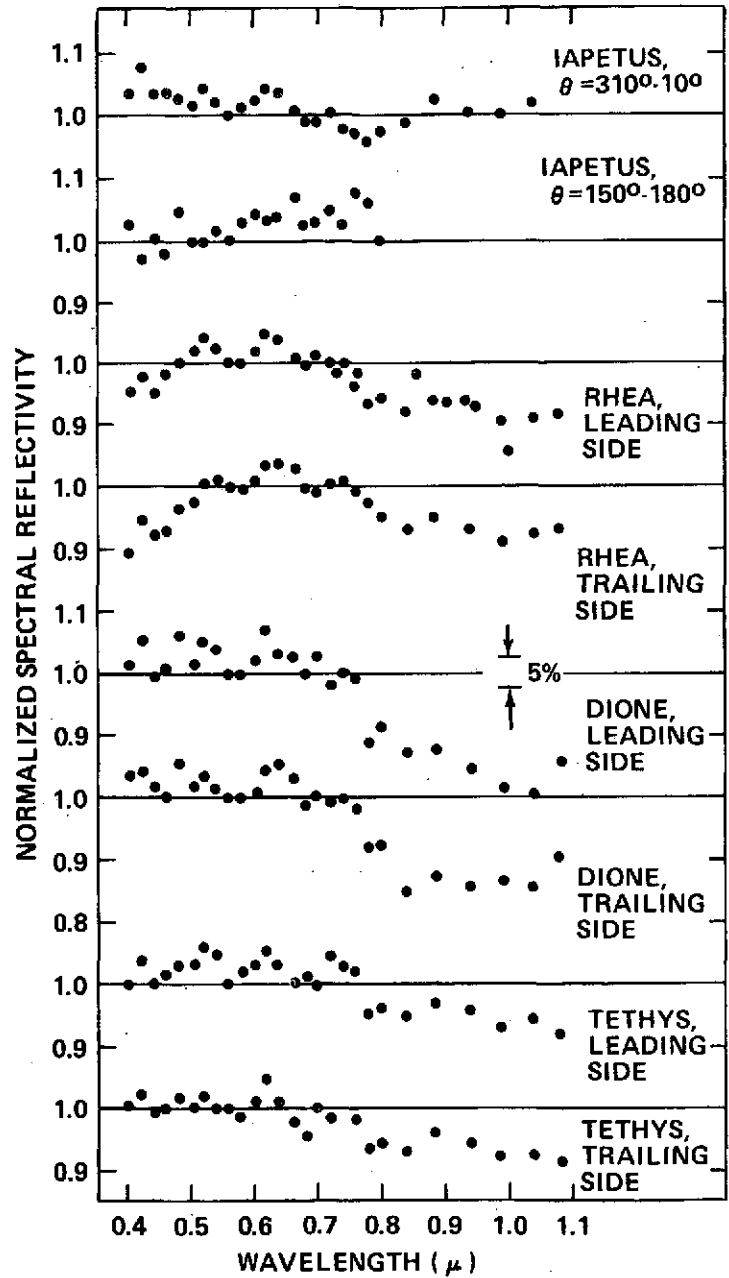
Figure IIIa is from Johnson and McCord (1970) and shows the

### GALILEAN SATELLITES



(a)

### SATURN'S SATELLITES



(b)

FIGURE III. Spectral reflectivity from 0.30 to 1.10  $\mu$  for (a) the Galilean satellites of Jupiter (Johnson and McCord, 1970), and (b) Iapetus, Rhea, Dione, and Tethys of Saturn (McCord et al, 1971). The curves are normalized to unity at 0.56  $\mu$ .

normalized spectral reflectivity of the four Galilean satellites. Io is very red, with a steep slope in the reflectivity from 0.4 to 0.7 $\mu$ . The other satellites are more nearly flat in this range. Spectral absorption features are found at 0.5-0.6 $\mu$  for Io only. Both Io and Callisto show a weak absorption near 0.85 $\mu$ . A decrease in reflectivity longward of 0.95 $\mu$  is much weaker in J I than in J II-IV. Such spectral features are diagnostic of surface composition (Adams, 1968; McCord and Adams, 1969), but in these cases the interpretations are not yet definitive. The Galilean satellites show spectral reflectivities suggestive both of ice and of rock or dust on their surfaces.

Newburn and Gulkis (1973) use the data of Johnson (1971) to compute geometric albedos (the ratios of average luminence at full phase to that of a perfectly diffusing - i.e., Lambertian - sphere) for the Galilean satellites. Figure IV is plotted from their Table XV, using the radii given in their Table XI and an assumed visual magnitude for the sun of  $V = -26.8$ . Not only is Io very red, but it has a very high red and near-infrared geometric albedo. J II (Europa) shows a high albedo in the visible red, but this decreases rapidly beyond 1.1 $\mu$ . Callisto (J IV) is very dark, and Ganymede is intermediate between J II and J IV over the range 0.4 to 1.1 $\mu$ .

The spectral reflectivities of the larger satellites of

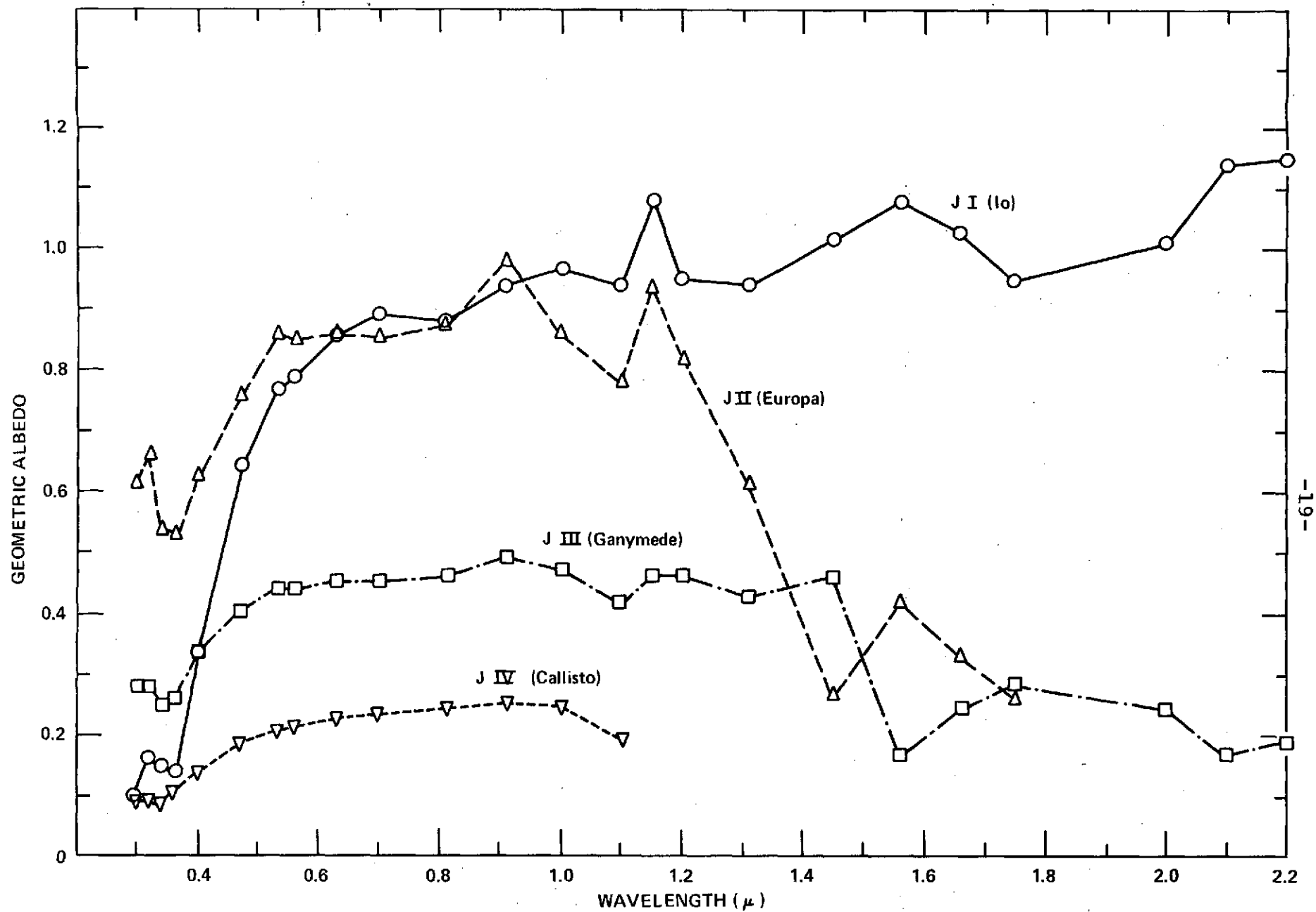


FIGURE IV. Geometric albedo of the Galilean satellites of Jupiter. (Based on Table XV of Newburn and Gulkis, 1973).



Saturn are quite different, as shown in Figure IIIb. Tethys, Dione and Rhea have curves that are flat to within 15% from 0.4 to 0.8 $\mu$  (McCord et al., 1971). These characteristics are consistent with water and/or ammonia ice (Kieffer, 1970). Rhea shows a downturn in reflectivity shortward of 0.4 $\mu$ , which the others do not. Only small changes are noted from one hemisphere to the other. The spectrum of Titan is quite different, but is compatible with the presence of a methane atmosphere (Kuiper, 1944).

The near infrared contains spectral features due to waterfrost at 1.6 and 2.0 $\mu$  (Kieffer, 1970; also unpublished). The strength of these features depends on particle size and the presence of impurities, but they dominate the spectrum when present. Pilcher et al. (1972) have identified water frost in the near-infrared spectra of J II, J III and J IV, and possibly J I as well. They suggest up to 70% of J II (Europa) - perhaps 100% of the near (leading) side - is covered by water ice. Ganymede (J III) has 20-65% and Callisto (J IV) has perhaps 5-25% frost cover. Fink et al. (1973) confirm the extensive H<sub>2</sub>O frost on J II and III, but find no infrared absorptions for J I. They suggest that surface dust is masking the spectral features. Callisto is also covered by dust but patches of ice do show through.

Several authors have published infrared brightness tem-

peratures for the large Galilean satellites and Titan (Murray et al., 1964; Gillett et al., 1970; Allen and Murdock, 1971, Morrison et al., 1972; Hansen, 1972), and some data exists for Rhea and Iapetus as well (Murphy et al., 1972). Table VI below is derived from Morrison et al. (1972).  $T_b(x)$  refers to the blackbody temperature at wavelength  $x$  for an object of the satellite's size at the appropriate distance from the sun. The observed temperatures are in general less than the blackbody temperatures, suggesting the surface emissivity is less than unity.

TABLE VI. INFRARED BRIGHTNESS TEMPERATURES  
FOR TITAN AND THE GALILEAN SATELLITES

	T(20)	$T_b(20)$	T(11)	$T_b(11)$
J I Io	127±3	139±4	138±3	142±4
J II Europa	119±3	139±4	129±3	142±4
J III Ganymede	134±4	146±3	138±3	149±4
J IV Callisto	149±4	150±4	155±3	153±4
S VI Titan	93±1	113±5	123±3	116±6

The high temperature for Titan at  $11\mu$  has led to the suggestion of a significant greenhouse effect (Sagan and Mullen, 1972; Pollack, 1973; Sagan, 1973), which may require a second major constituent for the atmosphere (see Trafton, 1972b).

Hansen (1973) and Morrison and Cruikshank (1973) use 10 and  $20\mu$  eclipse data to derive thermal inertias for the

Galilean satellites. The thermal inertia is the quantity  $(K\rho c)^{1/2}$ , where  $K$  is the thermal conductivity and  $\rho c$  is the heat capacity per unit volume. The units are  $\text{ergs cm}^{-2}\text{sec}^{-1/2} \text{ }^{\circ}\text{K}^{-1}$ , or if multiplied by  $2.4 \times 10^8$ , the units become  $\text{cal cm}^{-2}\text{sec}^{-1/2} \text{ }^{\circ}\text{K}^{-1}$ . Also frequently quoted is the thermal parameter  $\gamma = 1/\sqrt{K\rho c}$ . The above authors disagree on the value derived for  $I_0$  at  $10\mu$ , but both require a two layer model to match the cooling and heating curves of these satellites. A thin, low conductivity layer overlies a much thicker, high conductivity region. Figure V is from Morrison and Cruikshank (1973) and compares a two-layer model and a homogeneous model for Callisto (J IV). The thermal inertias derived by these authors are given below, together with the approximate brightness temperature at  $20\mu$  (Morrison et al., 1972).

These values are low compared to the Moon, with a thermal inertia of  $8 \times 10^{-4} \text{ cal cm}^{-2}\text{sec}^{-1/2} \text{ }^{\circ}\text{K}^{-1}$  ( $\gamma=1250$ ). A porous rock like pumice has  $40 \times 10^{-4}$  ( $\gamma=250$ ) while typical terrestrial rocks have  $700 \times 10^{-4} \text{ cal cm}^{-2}\text{sec}^{-1/2} \text{ }^{\circ}\text{K}^{-1}$  ( $\gamma=14$ ) (Kaula, 1968).

Polarization studies by Veverka (1971) suggest J I-III are covered by a bright, transparent, multiple-scattering material such as frost. Callisto has a darker, particulate surface, similar to the moon. It must be emphasized that the maximum solar phase angle achieved by Jupiter and its satellites as seen from the earth is  $12^{\circ}$ . While this is sufficient to reveal the presence or absence of a negative branch, no information is available on the crossover angle or for the linear part of the polarization curve. For the satellites of Saturn, the situation is even worse, yet

FIGURE V. Comparison of two-layer and homogeneous models for eclipse cooling and heating curves at 10 and 20  $\mu$ . The two layer model fits best for Callisto. (Morrison and Cruikshank, 1973).

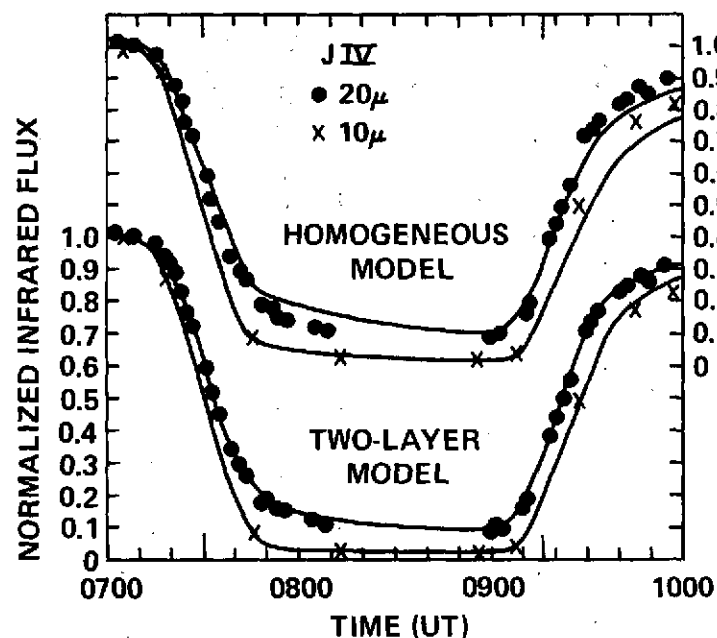


TABLE VII. THERMAL INERTIAS FOR THE GALILEAN SATELLITES

	T (20 $\mu$ ) °K	THERMAL INERTIA (K $\rho$ c) <sup>1/2</sup>		$\gamma = 1/(K \rho c)^{1/2}$
		ergs/cm <sup>2</sup> sec <sup>1/2</sup> °K	cal/cm <sup>2</sup> sec <sup>1/2</sup> °K	cal <sup>-1</sup> cm <sup>2</sup> sec <sup>1/2</sup> °K
J I Io	127°	$(1.3 \pm 0.4) \times 10^4$	$3.1 \times 10^{-4}$	$3200 \pm 1000$
J II EUROPA	119	$< 4 \times 10^4$	$< 10 \times 10^{-4}$	$> 1000$
J III GANYMEDE	134	$(1.4 \pm 0.2) \times 10^4$	$3.4 \times 10^{-4}$	$3000 \pm 400$
J IV CALLISTO	149	$(1.0 \pm 0.1) \times 10^4$	$2.4 \times 10^{-4}$	$4200 \pm 400$

Zellner (1972b) has suggested an albedo difference of factor 6 for the two hemispheres of Iapetus based on the polarization minimum. This is in agreement with the light curve observations (Millis, 1973).

Titan is the only satellite whose atmosphere is massive enough for ground-based spectroscopic detection with current techniques. Kuiper (1944) identified methane absorption features in the spectrum of the satellite, but Trafton (1972b) has argued for the presence of another bulk constituent, and has apparently detected  $H_2$  spectral features (Trafton, 1972a). Morrison et al. (1972) point out that the low infrared brightness temperature at  $20\mu$  could be due to absorption by  $H_2$ , but that nearly one atmosphere of the molecule would be required. The temperature at  $11\mu$  is higher than expected from equilibrium considerations, and this has led several to suggest the presence of a greenhouse effect in the atmosphere (Sagan and Mullen, 1972; Pollack, 1973). In some models, this greenhouse produces surface temperatures in excess of  $125^\circ K$  (Sagan, 1973). Danielson et al. (1973) believe the atmosphere of Titan may contain an inversion layer due to the absorption of solar ultraviolet radiation by small "dust" particles in suspension, and suggest that no greenhouse effect is required to explain the high 11 micron brightness temperature. Finally, polarization studies (Veeverka, 1973; Zellner, 1973) suggest the presence of an opaque cloud layer,

which is in agreement with the lack of detail reported by visual observers (Lyot, 1953; Dollfus, 1961).

Pioneer 10 radio occultation by Io suggests the presence of an ionosphere for this satellite (Kliore et al., 1974). The inferred neutral atmospheric surface pressure is estimated to be  $10^{-8}$  to  $10^{-10}$  bars. This is approximately the amount required by Sinton (1973) to explain the post-eclipse brightening of Io, and is well within the upper limits set by a stellar occultation of  $\beta$  Scorpii C by Io (Smith and Smith, 1972). The recent detection of sodium emission from Io by Brown and Chaffee (1974) also suggests at least a temporary atmosphere derived from the satellite's surface, although the mechanism is not at all clear (McElroy et al., 1974; Matson et al., 1974). Ganymede, the largest and most massive of Jupiter's satellite, occulted the star SAO 186800 in 1972, with the result of suggesting an atmosphere with surface pressure some  $10^{-3}$  millibars (Carlson et al., 1973). No other satellites in the solar system are known to possess atmospheres.

#### IV. MODELS OF THE SATELLITES

Little is known of the internal structure of the satellites of the giant planets. Because the masses and radii of most of these objects are so uncertain, mean densities are known in some cases to only 50%. Accurate densities

are a necessary prerequisite to the construction of interior models, for they limit the composition range available to the satellite. Densities of 3 or greater are those of rocky (silicate) objects; bodies dominated by ices would have densities of 2 or less. The greater distance of these satellites from the sun suggests they should contain a larger fraction of volatiles as ices than is present in the inner solar system (Cameron, 1973a,b; Lewis, 1973). Likewise, the apparent density decrease in the Galilean satellites with increasing distance from Jupiter places constraints on the percentage of ice in each satellite, and may provide clues about the thermal gradient in the proto-jovian system.

Lewis (1971a,b) has constructed models of icy satellites that suggest a "muddy" core of silicates, an extensive, melted, nearly isothermal mantle of ammonia-water, and a thin, weak, brittle crust of water ice. Internal heating causes convection in the slushy mantle, which keeps the ammonia-water mixture at or above the melting point. His models depend both on the radius of the satellite (which specifies the thermal gradient) and on an initial density which determines the composition of ice, silicates and radioactive elements.

The apparent upward revision in the densities of two of the Galilean satellites by Pioneer 10 tracking data (Anderson et al., 1974; Gehrels, 1974) suggests that Lewis (1971b)

models may be appropriate only for J III (Ganymede) and J IV (Callisto), whose densities are reported at 1.94 and 1.65 gm/cm<sup>3</sup> respectively. Europa (3.04 gm/cm<sup>3</sup>) now appears as a more familiar rocky object, and Io (3.48 gm/cm<sup>3</sup>) seems closer to the silicate objects Mars and the Moon than to an ice-like body. If the densities given in Table II are to be believed (see text), then several of the satellites of Saturn (Mimas, Enceladus, Tethys, Rhea and Iapetus) are of the exotic form proposed by Lewis, while Dione and Hyperion are "moonlike" and Titan is intermediate. Because of the uncertainties in the measurements of these masses and radii, it is only speculation at this point as to the structure of these satellites.

More observational data is available on the surfaces of the satellites. Non-uniform surfaces are reported by visual observers (Lyot, 1953; Dollfus, 1961) for those satellites large enough to show a visible disk. Variations in brightness with orbital phase are known for the large satellites of Jupiter (Harris, 1961; Johnson, 1971) and for the brighter satellites of Saturn (McCord et al., 1971; Millis, 1973), with the exception of Titan (Blanco and Catalano, 1971).

Io is the reddest satellite in the solar system (Harris, 1961) and its spectral reflectivity curve is unlike those of



the other Galilean satellites (Johnson and McCord, 1970). A weak absorption feature occurs at  $0.5$  to  $0.6\mu$ , with other depressions at  $0.85$  and longward of  $0.95\mu$ . A steep decrease in reflectivity occurs at wavelengths shorter than  $0.5\mu$ . These characteristics are unlike those seen for the Moon (McCord et al., 1972), Mars (McCord and Westphal, 1971) or the asteroids (Chapman et al., 1973). The outer three Galilean satellites have flatter reflectivities from  $0.4$ - $0.8\mu$  (Johnson and McCord, 1970), a characteristic of ices (Kieffer, 1970), although they too decrease in reflectivity shortward of  $0.5\mu$ . The least dense of these large objects, Callisto, has a weak absorption at  $0.85\mu$  and is a relatively dark object.

Polarization data suggests a thin, bright, transparent layer on the surfaces of J I, II, and III, but J IV (Callisto) is dark and similar to the Moon (Veverka, 1971). Pilcher et al., (1972) find extensive water frost on J II and J III, in agreement perhaps with the polarization results. Io has little frost, and Callisto has only patches showing through a dust layer (Fink et al., 1973). Gillett et al. (1973) find a very high infrared albedo for Io, suggestive of ice, not bare rock. Thermal inertias (Morrison and Cruikshank, 1973) seem to require a thin, low conductivity layer (frost?) overlying a much thicker region of higher thermal conductivity (rock?).

The surfaces of the Galilean satellites are complex, inhomogeneous and variable in spectral reflectivity with longitude. There is sometimes contradicting evidence for both ice and for dust or rock. More information is needed to clarify the situation.

The unusual post-eclipse brightening of Io is still unexplained. Binder and Cruikshank (1964) reported a 15 minute long increase in the brightness (0.1 magnitudes) upon re-emergence of the satellite from Jupiter's shadow. Attempts by others to observe this phenomenon have met with both success and with failure. Some have concluded the effect does not exist (Franz and Millis, 1970), while others believe it is real (Johnson, 1971; O'Leary and Veverka, 1971). Recently Cruikshank and Murphy (1973) have suggested the brightening is intermittent but real. Sinton (1973) believes a condensible ammonia atmosphere, responding to seasonal orbital changes, can explain not only the post-eclipse brightening and non-brightening, but also the two layer modeling for the eclipse curves (Morrison and Cruikshank, 1973) and the disagreement between the 10 and 20 $\mu$  brightness temperatures observed for Io. His model predicts post-eclipse brightening during the Fall 1973 opposition, but Millis et al. (1974) have been unable to detect the phenomenon. It may be possible to explain the erratic history of the events by surface morphology (Frey, 1974).

The brighter satellites of Saturn have spectral reflectivities that differ from those of the Galilean satellites (McCord et al., 1971). The curves are generally flat in the visible, with a decreasing reflectivity in the red. Rhea shows a drop in reflectivity shortward of  $0.5\mu$ . These are characteristics of ices, not silicates (McCord et al., 1971; Kieffer, 1970). There are small spectral changes with rotation, and brightness variations are known to exist. Iapetus shows a six-fold variation in albedo (Zellner, 1972b), although it changes little in color with rotational phase (Millis, 1973). The model proposed by Cook and Franklin (1970), in which the leading dark side is exposed rock (resulting from meteoroid erosion of an icy layer), finds little support in the limited spectral coverage by McCord et al. (1971). Millis (1973) suggests the leading darker side has a different solar phase function than the trailing side, and Zellner (1972) reports polarization characteristics suggestive of a compositional difference from one side to the other. More observations are necessary to detail the surfaces of these satellites.

Johnson and McGetchin (1973) have examined the problem of topographic relief and shape for a variety of objects in the size and density range expected for satellites of the outer planets. Small satellites are expected to retain the original topography over time scales approaching the age of the solar

system. For larger objects, internal evolution will affect topography. Moonlike bodies such as J I and J II probably retain ancient topography generated after differentiation; ice-like objects the size of the Galilean satellites deform by creep and topographic relaxation should occur in a few million years. These bodies retain only the most recent record of processes shaping their surfaces, while J I and J II perhaps preserve a much more lengthy history. Because of the uncertainties in the sizes and masses of the satellites of Saturn, little can be said about the expected relief on these objects.

Stellar occultation of  $\beta$  Scorpii C by Io has been interpreted by O'Leary and Van Flandern (1972) as indicating a triaxial figure for this satellite, with the long axis ( $r_a = 1829.2$  km) pointing towards Jupiter. They suggest a value of  $a-c \approx 20$  km, and compute rotational and tidal bulge coefficients for all the Galilean satellites assuming a homogeneous, hydrostatic fluid in synchronous rotation about Jupiter. If occultation timing residuals can be attributed to surface irregularities, there is a suggested 3 km deep depression on one limb of Io.

In summary, the collected observational data on the satellites of the outer planets suggests a great variety of possible models. Little is known about the composition,

internal structure or surface morphology of these objects. Some are as large as our Moon; others seem to be very small. The regularity of the orbits of many of these satellites suggests they offer important clues about the origin and possibly the early evolution of the solar system. Extensive ground-based and space probe studies of the outer planets and their satellites is needed before a complete understanding of our solar system can occur. These small objects, with their wide variety of sizes, surfaces and interiors, should be a high priority item for future study in the search for clues about the basic properties of the solar system.

PART II

FUTURE STUDIES OF THE OUTER PLANET SATELLITES

## V. FLYBY/ORBITER MISSIONS TO THE OUTER PLANETS

Space probes directed to the outer planets offer the possibility of a close, detailed investigation of the surfaces of the satellites of these planets. The major advantages of such close flybys and/or orbital missions to these objects can be described in terms of three major experiments: (a) imaging, (b) infrared spectroscopy/radiometry, and (c) celestial mechanics. Ultra-violet photometry and/or spectroscopy and polarimetry offer additional information, especially for the atmospheres of satellites. We discuss these three major areas below:

(a) IMAGING OF SATELLITES. The advantage of a flyby is obvious: from the Earth the satellites of the outer planets present barely discernible disks; no spatial information is available except for the Galilean satellites of Jupiter and Titan of Saturn, where surface coloration has been reported by visual observers. Detailed spatial resolution of satellites offers two important kinds of information: direct measurement of satellite diameters, and surface mapping of structural landforms.

Diameters are important for determination of the density of these objects. It is important to know the density in order to construct interior models and to place gross limits on the available composition (and therefore surface materials) for the satellites, which are expected to become more volatile-rich with increasing distance from the sun. Interior models are tied to the models for surface processes which may be invoked

to explain observed surface features.

Surface mapping provides detailed clues about the composition, origin and evolution of the surface, and about processes affecting the surface at the present time. Mapping albedo patterns provides regional classification of major units: in the case of the moon albedo correlates very well with geology, composition and age. However, this correlation is not universal, and on Mars there is no simple correlation between albedo and surface morphology (Frey, 1973). On non-vegetated areas of the Earth, some correlation does exist between surface coloration and gross structure/composition (Lowman and Tiedemann, 1971). The situation is therefore not unique, and albedo must be compared with the surface morphology.

Surface structures reveal much about the satellite. The presence of large shield volcanoes or vast mare basalt flows such as found on Mars would suggest two different kinds of volcanic activity, which in turn is suggestive of differentiation. The shape and size and detailed structure of impact craters provide clues about the viscosity and structural strength of the crustal materials present, and the degree to which isostasy is important. The presence of tensional features or massive rift valleys points to interior tectonic processes, which can be related to interior modelling of the satellite. The degree of ice cover on a particular satellite suggests compositional and evolutionary limits, and may offer



clues about the outgassing rates. All of these features require close-in imaging to be recognized and studied.

Surface processes also are revealed by detailed imaging of surfaces: crater counts offer the relative dating of features, and therefore outline the history of surface events. The degree and morphology of cratering further offers clues about the properties of the different crustal materials present. The presence of erosion, mass wasting, filling and deformation by creep, tectonic or volcanic processes, condensation or whatever process will also provide information on the structure and history of the satellite.

In short, detailed imagery of satellites offers a wealth of data, not only of itself, but also by providing a context in which other data can be interpreted, as discussed below.

(b) INFRARED SPECTROSCOPY/RADIOMETRY. The infrared region of the spectrum contains many spectral features which are diagnostic of composition. Solid surface reflection spectra can provide discrimination of the major rock types present on a satellite, the distribution of these, and perhaps the degree of mixing or modification of the major crustal rocks. Ices too show important spectral features diagnostic of composition in this wavelength region. It should be possible to correlate the surface composition with the observed geologic landforms detected by imaging experiments, and thereby infer much about the processes which generated and re-worked the surfaces

of the satellites.

The presence of an atmosphere may also be detected by infrared spectroscopy, as many of the expected molecular species have spectral features in this part of the spectrum. If the atmosphere is sufficiently thick, pressure mapping can be accomplished from an orbiter, and these altitude contours correlated with imaged topography of the satellite. Pressure-temperature profiles of the atmosphere will reveal information on its structure and diurnal changes.

Radiometry of the surface can provide thermal maps that may be correlated with imagery to suggest subsurface conditions. Detailed heating and cooling curves can provide data on the thermal inertia, which, although not a unique determination of composition, is at least suggestive of the compaction of the surface. The percentage ice cover on a given satellite can be mapped, and this should provide information on the current processes affecting the surface.

Compositional information concerning the surfaces of the satellites is important to an understanding of the evolution of these objects: the presence of differentiation products implies a past period of internal melting, which in turn may indicate the presence of radioactive species inside the satellite. The composition of satellites is expected to become more volatile rich with increasing distance from the sun: the presence of different surface compositions among satellites of

the same system would put constraints on the original conditions of the protoplanet and on the thermal and perhaps density gradient within the system at the time of formation. The presence of outgassing products places further limits on the interior models. The cosmogonic and evolutionary implications make the determination of surface compositions a high priority item for future space missions.

(c) CELESTIAL MECHANICS. Flybys offer perhaps the best determination of the mass of small satellites. This parameter is essential for interior modelling of the satellites, for the mass together with the diameter (from imaging) determines the density of the body. Densities are a boundary condition on composition and therefore on interior processes: objects made exclusively of water ice (density $\sim$ 1) are not expected to have metallic cores, while large silicate objects (density $>$ 3) could very well have differentiated sometime in their history (as in the case of the moon). This essentially free information (accurate radio tracking of the spacecraft is all that is required) is perhaps the only accurate determination of the mass of these objects available, and is essential for an understanding of their interiors, evolution, and the possible processes that could shape the surfaces.

## VI. SCIENTIFIC VALUE OF SATELLITE STUDIES

There are a number of important scientific problems whose

solution may benefit from a detailed study of the satellites of the outer planets.

(a) ACCRETION IN THE SOLAR NEBULA. The details of the satellite and planet formation process are still unclear. It is generally accepted that the formation of the planets was linked to the formation of the sun itself; no intruding body need be invoked to stimulate the process of planetary creation. But there is little agreement on the actual process, or even on the conditions of the solar nebula at the time when the process took place. It is not yet clear, for example, whether the original mass of the proto-planetary disk was equal to or much greater than the combined mass of the planets which exist today (see Cameron, 1973a).

Likewise there is controversy over the timing of the accretion process. Lewis (1974) has summarized the two schools of thought in a popular way. The major point is whether accretion proceeded slowly enough that condensation products had time to react with the uncondensed material (e.g., Fe reacts with  $H_2S$  to form troilite), or whether accretion occurred rapidly so that products of condensation became parts of a zoned planetary body as soon as they achieved a condensed form. Lewis (1974) prefers the former model (which he calls the "equilibrium-condensation model") but points out that the structure of planets and satellites permits testing of these two different points of view. Because the outer planets are

essentially gaseous, it is to the satellites we must turn to understand the implications of the two models. Structure as a function of size and distance from the primary and the sun provides important clues; information on the structure can be obtained by the investigations described above.

(b) PLANETARY EVOLUTION. While it is not possible to divorce planetary evolution from the accretion process, detailed studies of the satellites have the potential of revealing much about the post-accretion development of these objects.

Io and Europa seem to have lunar densities, and are to be considered silicate-rich objects (see Physical Properties section above). It is of interest to know whether, like the Moon and Mars, these objects have differentiated, and to what extent this internal evolution has led to volcanic and tectonic activity. If they are differentiated, then the role of heating of planetary interiors by accretionary processes and radioactive decay will be underscored; because of their greater distance from the sun, it is not likely that a high temperature phase in the proto-sun or an enhanced solar wind during the early years of formation could contribute as much to these objects as it might have to the Earth, the Moon and even perhaps Mars. Studies of the composition and morphology of the surfaces, the internal mass distribution and the occurrence of atmospheres, if any, will all place limits on the models that can be invoked for these two objects.

On the other hand, Ganymede and Callisto have a much lower density, and Lewis (1971a) has proposed a much more exotic structure for such objects. These icy satellites would be completely unlike any object so far encountered, and besides the intrinsic interest in a new class of objects, the occurrence of these in the same system with two high-density, apparently lunar-like satellites should place constraints on models of the early proto-jovian system. Both thermal and density gradients in the proto-satellite disk around Jupiter may be specified, and this in turn may aid study of the accretion process.

If differentiation has occurred, the pattern of its expression is important. If a global crust exists as a result of the internal melting, then support is found for the concept that this is the natural cause of the formation of the Earth's continents, as proposed by Lowman (1973). On the other hand, the occurrence of patchy differentiation products might suggest that continents form as tiny nuclei which grow by accretion at the boundaries. Safronov (1972) has suggested that continents result from localized heating due to infalling planetesimals. The impact of such large objects may also play a role in the orientation of the rotation axis, and, with sufficient data from a large number of objects, it should be possible to test this point. It will, for example, be of interest to compare the rotation axis orientation of the satellites of Jupiter,

although the strong tidal attraction of Jupiter may confuse the picture.

In summary, the satellites of Jupiter and Saturn offer additional examples of planets, but of planets whose formation was in a part of the solar nebula where conditions were completely unlike those from which the terrestrial planets formed. Studies of these objects, as suggested above, will shed much light on important cosmological and cosmogonic problems, such as those discussed above. The information derived from these studies is important not only for an understanding of the formation of planets, but of the solar system as well.

## VII. THE ROLE OF GROUND-BASED STUDIES

Ground-based studies of the satellites of the outer planets suffer two severe problems: (1) the small disk sizes seen from the Earth allow no spatial resolution of the satellites, and (2) many important wavelengths are denied to observers who work beneath the Earth's atmospheric blanket.

Flyby and/or orbital missions to the outer planets and their satellites have the advantage of increased spatial resolution. This allows a detailed study of the surfaces of these objects, which should yield clues about the composition and evolutionary history. For example, the presence of a shield volcano like Nix Olympica of Mars would be good evidence for

differentiation and past volcanic activity. Such observations can, of course, be made only from the vicinity of the body. Even mapping of the surface into major albedo units requires at least a twenty-fold decrease in the distance to the jovian satellites (at this separation, Io would have an angular size approximately equal to that of Mars as viewed from the Earth). For the satellites of Saturn, Uranus and Neptune, the situation is even more severe.

Likewise ground-based astronomers cannot observe some of the important wavelengths required for a detailed understanding of the atmospheres and the surfaces of the outer planet satellites. Much important data can be obtained about the scattering in atmospheres by studies of the ultraviolet part of the spectrum. The Earth's atmosphere prevents wavelengths less than 3000 Å from reaching the ground. The important diagnostic absorption bands due to common rocks and minerals are found in the infrared, where observations from the Earth are either difficult or impossible. Detailed thermal mapping requires infrared detectors with a high spatial resolution. Many molecular constituents of atmospheres have important spectral features in the infrared region. Observations of this kind can be made only from spacecraft in the vicinity of the planet.

The single advantage held by ground-based observers is longevity. Flyby missions last at most a few days in the vicinity of a satellite system; the total time devoted to a



given satellite is measured in minutes, or, at most, hours (if the satellite is observed both during approach and during departure). These moments are important for the detailed view they give us, but that view may be of only a small and perhaps non-representative part of the surface. In a similar way orbital missions are normally confined to a single object because they lack the capability of plane changes. Usually the planet will be the target of these longer missions, and satellites will be observed only occasionally.

Terrestrial observers are restricted to whole-disk studies in a small spectral interval, but the long time base available provides the context within which the detailed mapping by spacecraft may be interpreted. Diurnal or longer term (seasonal or secular) changes will most easily be observed during systematic programs of long duration. Evolutionary variations will also be more easily recognized and interpreted if a long time base is available for comparison of the trend. It is more efficient to carry out comparative studies of a large number of objects from the ground than with spacecraft, where many may be needed to observe all the satellites of a given system.

Finally, because most of the solar radiation reflected by these objects does lie in the visible part of the spectrum, no detailed, systematic study of the satellites can be comprehensive unless the visible wavelengths are also studied.

Spectrophotometric observations of the reflected light from the satellites should be continued not only for the information available in these wavelengths, but also for the general context in which other data are interpreted, and for the long-term monitoring of changes that may occur.

## CONCLUSIONS

Although not always definitive, the data so far available on the satellites of the outer planets suggests both objects new to our experience as well as bodies which may be similar to the moon. Because their formation occurred in a region of the solar nebula where conditions were very different from those in which the terrestrial planets originated, studies of these satellites offers understanding of the basic problems of the origin and evolution of planetary bodies and of the solar system as a whole.

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